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Human kinematics and event control: on-line movement registration as a means for experimental manipulation

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In human movement and sports science, manipulations of perception and action are common and often comprise the control of events, such as opening or closing liquid crystal goggles. Most of these events are externally controlled, independent of the actions of the participants. Less common, although sometimes desirable, are event manipulations that are dependent on the unconstrained movements of participants. As an example, we describe a method we used previously to manipulate vision of basketball jump shooters on the basis of on-line registration of their own movements. The shooters wore liquid crystal goggles that opened or shut as a function of specific kinematic features of these movements. The novel aspect of this method is that the criteria for detecting movement patterns and performing the appropriate manipulations are adjustable to the specific sport context and the complexity and variations of the unconstrained movements. The method was implemented as a finite state machine: a computer system that can be used for pattern recognition. We discuss this method, how it works and the potential it has for studying perceptual-motor skills in sport. Furthermore, the results of the basketball experiment are briefly summarized and complemented with new analyses.

Keywords: basketball shooting, event control, experimental manipulations, liquid crystal goggles, movement registration.

Introduction

In the human movement sciences, there is a need for scientific experiments in natural settings with complex tasks. Developments in this field in the last two decades necessitate a reconsideration of the way in which experimental research is carried out. In particular, the view that moving human beings cannot be seen as isolated entities independent of the environment in which they act (Gibson, 1979) has repercussions for the way in which human movement studies should be set up. Similarly, the idea that perception and movement are different sides of the same coin, namely human action, has implications for carrying out research.

For example, perception studies in sport sciences have used slide, film or video displays to which participants provided perceptual judgement as a representation of the most appropriate action (see Williams *et al*., 1999). Often this research fitted well with the contemporary technological developments. We now know that despite the valuable insights that this research has provided, it did not test perception in action. Complex perceptual-motor skills are context-specific. Thus, to gain insight into essential characteristics of the skilled execution of tasks, such as basketball jump shooting, tenpin bowling or playing a forehand in tennis, it is important to reproduce faithfully the performance environment (Abernethy *et al*., 1998).

Research has shown that testing in ecologically valid environments may provide results that differ from those found in more restricted settings, such as seen in laboratory tasks. For example, perceptual judgement studies provide different information to studying perception in action (e.g. Oudejans *et al*., 1996a; Pagano *et al*., 2001). Oudejans *et al*. (1996a) found that perceptual judgements of whether a fly ball is catchable were better when participants were allowed to move compared to when they had to make their judgements from a stationary position (as is often done in experimental settings), a finding that was replicated with respect to judging whether a busy street was

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crossable while walking or while standing still (Oudejans *et al.*, 1996b). Pagano *et al.* (2001) found systematic differences in perceived distance between judgements using verbal responses and using manual reaches. This is related to the current debate in the literature about different functional pathways for the processing of visual information in the central nervous system. Recent developments in neuro-physiological and neuro-psychological research have identified two anatomically and functionally distinct streams of visual information processing, the dorsal and the ventral stream (Milner and Goodale, 1995; Michaels, 2000; Rossetti and Pisella, 2002). Whereas the dorsal stream appears to be mainly involved in the perceptual control of movements (i.e. vision for action), the general function of the ventral stream appears to be perception and recognition of objects and events (i.e. vision for perception). Although it is unlikely that under normal conditions the dorsal and ventral streams act independently (Milner and Goodale, 1995; Rossetti and Pisella, 2002), it is crucial in studying vision in sport to guarantee the involvement of dorsal stream processes in the experimental task. However, this is easier said than done. It is difficult to guarantee scientific rigour and experimental control with complex perceptual-motor tasks in (quasi-)field settings.

The aim of the present study was to introduce and describe an elegant and promising method for testing complex perceptual-motor behaviour while maintaining experimental control and scientific rigour. The method was used in a recent study of the role of vision in basketball jump shooting (Oudejans *et al.*, 2002) and has much potential for other studies of perceptual-motor skills in sport. Before providing the details of our basketball application, we first introduce the problem of experimentally manipulating events in sports and the human movement sciences.

The control of movement-dependent event manipulations

Experimental manipulations in the human movement sciences often involve the control and registration of events in the actor–environment system. Events can be defined entirely externally – that is, independent of the movements of the actor, who could be a juggler, a basketball player, a Parkinson's patient or any other moving human being. One example of such an event manipulation is the opening and closing of liquid crystal goggles during the execution of perceptual-motor skills. The timing of the opening or shutting of these goggles may be controlled entirely externally with pre-set time intervals imposed by a computer (van Santvoord and Beek, 1994) or simply by a key-press by one of the experimenters (Starkes *et al.*, 1995).

Sometimes, the external control of events is not desired. Instead, event control on the basis of the movements of the participant is preferred or even required. In such cases, the movements of the participant (co)determine the real-time events in the environment. An example is provided by the studies of Post and colleagues (Post *et al.*, 2000a,b) in which rhythmic forearm movements around a single axis of rotation were perturbed using an electromotor. The perturbations applied were a function of the kinematic and kinetic properties of the performed movements. In this example, the movements made were constrained by the apparatus, which forced the movements to occur around a single axis of rotation.

In sport, however, the movements are not constrained, as for example with a freely moving basketball player. A method for controlling events in a more complex sport setting is the use of a switch. For example, Oudejans *et al.* (1999) used a foot-switch to determine the movement initiation time of participants catching fly balls on the run. However, in some cases, the trigger of events is not optimally related to pressure (or release thereof) on the floor or some other surface, but on, for example, the *relative motion* of a free-moving arm relative to the head (as in our basketball example described below). Also, movement patterns may vary from trial to trial or between participants. The algorithms for detecting movement patterns that could be used to trigger events can become quite complex or even difficult to discover, especially when the specific context and order of the movements co-determine when the event should occur. One way to get a better grip on the variability of movement patterns in movement-dependent event control is to process kinematic data in real time. For processing kinematic data with acceptable delays, the information about movements is reduced to only a few points in three dimensions (to obtain a schematic representation of the movements of, for instance, the knee, hip or elbow). Event control then involves real-time pattern recognition of these three-dimensional movement representations and translation of these data to initiate an event.

An interesting example of recent movement-dependent manipulations is virtual reality. Virtual reality, however, has a few disadvantages that make it less suited for some of the purposes of research on human movement and sport (see Durlach and Mavor, 1995). First, reverting to the importance of sport and task specificity, it is still difficult to simulate the complex information patterns governing sport performance (Zaal and Michaels, in press). Although the stimulus display may approach ambient information, in most cases the display is limited to surfaces below, to the left, right and in front of the person without displaying information above the head or behind the participant. Furthermore, delays in the display (e.g. 80–200 ms; Zaal and Michaels, in press) are often too long to faithfully simulate the sport-specific perceptual information that is so crucial for expert performance (Durlach and Mavor, 1995). In addition, virtual reality systems are still constrained to a relatively confined space (e.g. the size of a virtual reality cave is $3 \times 3 \times 3$ m), making the investigation of larger movements, such as in a basketball jump shot or ten pin bowling, impossible.

Thus, a number of studies have investigated the effects of applying various types of stimuli and perturbations to movements in a manner that was contingent on the movement itself (Forssberg *et al.*, 1977; Gottlieb and Agarwal, 1978; Forssberg, 1979; Brooke *et al.*, 1992, 1993, 1995; Cheng *et al.*, 1995; Staines *et al.*, 1997; Post *et al.*, 2000a,b). However, these studies focused on more laboratory-oriented tasks such as aiming and locomotion and were not conducted in a sport context. To manipulate events in a sport context on the basis of the movements of the actor, it is desirable that the criteria for detecting the movement patterns and performing the appropriate actions are adjustable to this sport-specific context, the complexity of the movements and the variations between the movements. Therefore, an open and flexible system is required that can be used in (simulated) real-life size settings in which unconstrained movements can generate events with minimal delay. Here, as an example, we describe a method we used previously (Oudejans *et al.*, 2002) to manipulate vision during basketball shooting on the basis of on-line registrations of the shooter's own movements using a finite state machine (for an explanation, see below). In the remainder of this paper, we first describe briefly the rationale and general method of the experiment. We then describe the hardware and software used to implement the finite state machine, the finite state machine itself and the limits and advantages of the method that was used. Finally, we summarize the results of our earlier study (Oudejans *et al.*, 2002) and complement them with additional analyses of the temporal patterning of the shooting movements.

Rationale and method of the basketball experiment

An important characteristic of expert behaviour in sport is the ability to attend to the right information sources at the right time while ignoring irrelevant and possibly distracting stimuli in the environment (Abernethy, 1996; Williams and Grant, 1999). Oudejans *et al.* (2002) examined the visual control of expert basketball players performing jump shots to gain insight into the temporal patterning of information pick-up during shooting.

Hitting a jump shot in basketball is an amazing accomplishment. While the body is in full motion, shooters make fast arm movements during their jump to propel the ball with a high curved trajectory to and through the hoop. Jump shots are often executed under pressure. In the midst of 'dividing' attention among fast moving fellow players and opponents, at some point in time the shooter has to look at the hoop to release a good shot (for gaze behaviour during the free throw, see Vickers, 1996). Since players have limited time to look at the hoop, an intriguing question is when and for how long a player should ideally see the hoop. Research by Vickers (1996) indicates that, to be successful, shooting players should look at the hoop for a relatively long time and before the final shooting movements are initiated. However, according to Oudejans *et al.* (2002), optimal gaze behaviour may be dependent on shooting style. A commonly used shooting style is the overhead-backspin style (Hamilton and Reinschmidt, 1997). Using this style, the ball is first elevated above the head, and thus above the line of sight, before the final shooting movements and release of the ball occur (Kirby and Roberts, 1985; Hay, 1993). This allows a player not only to look at the hoop before ball and hands move through the line of sight [as most of Vickers' (1996) participants did], but also after this moment from underneath the ball until ball release (see Fig. 1, top) (for more information on shooting styles, see Oudejans *et al.*, 2002). Do expert basketball players who shoot with a high style take advantage of the information that is available to them during the final moments before ball release? The answer to this question may have implications for the type of movement control – open-loop or closed-loop – that is used for taking jump shots.

Rather than recording gaze behaviour as is usually done in the visual search literature (e.g. Vickers, 1992, 1996; Williams *et al.*, 1994; Vickers and Adolphe, 1997; Savelsbergh *et al.*, 2002; see also Williams *et al.*, 1999), we investigated shooting performance of expert male high-style shooters with vision occluded either before or after the ball and hands moved passed the line of sight. By doing this we imposed constraints on vision that made visual information for shooting available and unavailable during specific phases of the shooting action. Thereby it was possible to determine not only whether late or early viewing was sufficient for accurate shooting with a high style, but also whether late or early vision was necessary.

In addition to late vision and early vision, as control conditions we tested shooting performance with full vision and no vision. Vision was manipulated by using Plato liquid crystal goggles (Translucent Technologies, Toronto, Canada) that were controlled on the basis of the shooter's own shooting movements. Movement registration of hand, heel and head were fed back on-

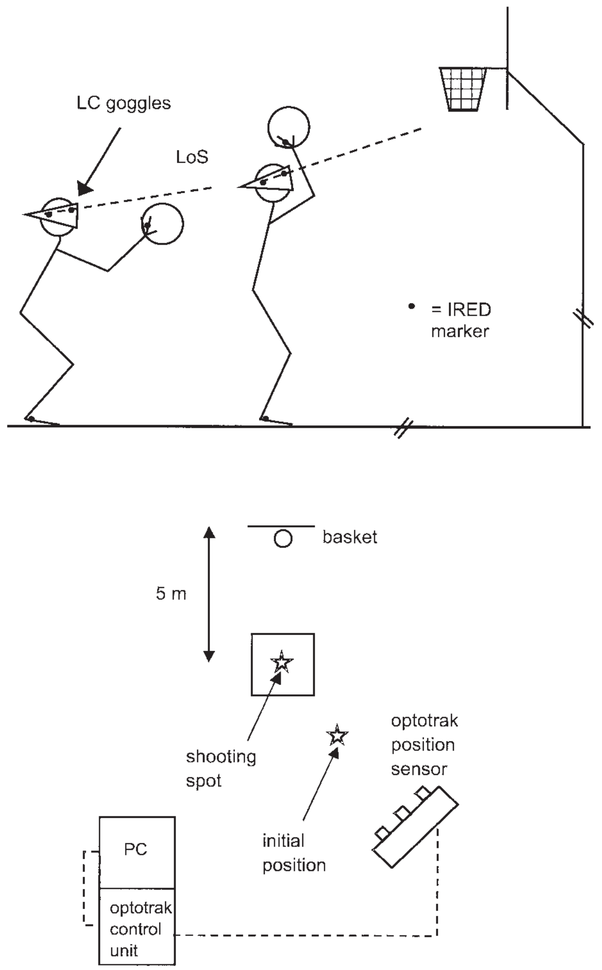

Fig. 1. (Top) Schematic representations (side view) of a shooter with a ball before (left stick figure) and after (right stick figure) the hands and ball passed the line of sight (LoS). (Bottom) Experimental set-up as seen from above.

line to the personal computer that used the data to shut or open the goggles (depending on their initial state) when hand and ball passed the line of sight.

Experimental set-up

A basket with a regulation backboard and rim (0.45 m diameter; height 3.05 m) was placed in a large laboratory (height 7.5 m). The distance from the basket to where the shot was to be taken was 5 m, slightly more than the free-throw distance. The initial position of the shooter was at a perpendicular distance of 6–7 m from the basket and about 1–2 m to the right of it (see Fig. 1, bottom). The task of the shooter was to take a jab step to the right, make a cross-over step to the left, make one dribble with the left hand, land in the centre of a 1 × 1 m square marked on the floor with white tape at about 5 m from the basket, jump up and take a jump shot. This shooting task would be an appropriate skill for an intermediate- to high-standard player, but would be difficult for novices. The main dependent variable was the number of hits in each condition.

Hardware

To allow control of the liquid crystal goggles on the basis of the shooter's movements, head movements, heel movements of the right foot and movements of the right hand were registered in three dimensions using OPTOTRAK 3020 (Northern Digital Inc., Waterloo, Canada), a motion measurement system with small active infrared emitting diodes (IREDs) or markers (www.ndigital.com/optotrak.html). OPTOTRAK detects the markers and for each calculates accurate three-dimensional positions in real-time. Marker identification is guaranteed at all times because the markers are activated one at a time. If markers go out of view, they are automatically identified by the system when they return into view due to this known sequential order. A sample frequency of 100 Hz was used. Two markers were placed on the right leg of the liquid crystal goggles, one just above the eye and one just in front of the ear. They were used as an indication of the line of sight (defined by the orientation of the head, irrespective of eye movements). One marker was placed on the right side of the right shoe near the heel and another was placed on the ring finger of the right hand (see Fig. 1, top).

The OPTOTRAK configuration used in our basketball experiment (Fig. 1, bottom) consisted of a PC host computer (Pentium II 233 MHz, 64 MB SDRAM with Windows98) with an interface card, an OPTOTRAK control unit connected by cable to the PC, a position sensor linked to the control unit, two strobe units and eight IRED markers. The position sensor was placed 5 m obliquely behind the shooting spot at a height of 2.65 m. The control unit and PC were positioned a few metres behind the shooting spot (Fig. 1, bottom).

Spatial accuracy

To reliably use the kinematic data obtained from OPTOTRAK, it is essential that measurements are accurate. Therefore, in separate sessions we determined the static and dynamic accuracy of the OPTOTRAK registrations using one position sensor. The procedure we used for measuring static spatial accuracy was as follows:

- One marker was attached to the moveable measuring face of a digital calliper.
- The position on the calliper was read from the digital display (accuracy 0.01 mm).

- The position of the marker was registered by OPTOTRAK for 2 s from 4 m.
- The marker was moved to another position (maximal displacement 0.15 m).
- The new position on the calliper was read from the digital display.
- The new position was registered by OPTOTRAK (for 2 s from 4 m).
- Distances between measured calliper and OPTOTRAK positions were compared.

This procedure was performed for different angles of orientation of the calliper relative to the viewing direction of the position sensor. Mean and maximum differences between calliper readings and OPTOTRAK registrations demonstrated that the registrations were very accurate, with mean errors of 0.007–0.108 mm and maximum errors of 0.011–0.152 mm (more details can be obtained from the authors).

To determine dynamic spatial accuracy, two IRED markers were attached to both ends of a rod 1.30 m long. The rod was translated and rotated through the measurement space. Registered change of length provided an indication of dynamic accuracy and linearity. The maximally registered change of length of the rod was 0.642 mm. Thus, using one position sensor, OPTOTRAK performance is good in comparison with other commercially available optical systems, such as video, Selspot and Vicon (see also Richards, 1999). Performance was sufficiently accurate for the manipulations of our basketball experiment, which also used one position sensor.

Software

The programming environment used to implement the basketball jump shooting application was LabVIEW (National Instruments, Austin, TX). Programming techniques for implementing finite state machines in LabVIEW are described by Bitter *et al.* (2001).

The basketball jump shooting application

Architecture: a three-layer model for running experiments

To create an open and flexible system for the basketball application, we designed a three-layer model in LabVIEW. The principles of this three-layer model for experimental research were developed by den Brinker and Coolen (1993; Den Brinker *et al.*, 1994). Layer 1 captures the management of the research design of an experiment. In this layer, it is easy to implement many experimental designs in a flexible way. The experimenter enters crucial information about the design – number and names of conditions and participants, number of trials per condition, randomization demands, and so on. On the basis of this input, a list of trials is generated. The order of the trials in the list matches exactly the prescribed design. Once this list is available, the experiment can be executed (semi)automatically.

The control of event manipulations, Layer 2, is hooked onto the management shell. In this layer, the specific event manipulations that will occur during one trial are implemented. As this layer comprises the event control on the basis of the movements of the actor, the central topic of this paper, it will be described in detail in the next section.

The third layer provides the interface with the hardware, in our case the drivers to OPTOTRAK and goggles. This layer is hooked onto Layer 2. In our basketball application, the communication with OPTOTRAK was simplified by a routine-based interface (OPTOTRAK Application Programming Interface) provided by Northern Digital.

Layer 2: manipulating vision in basketball shooting with a finite state machine

Layer 2 in the architecture was the layer at which event control was implemented as a finite state machine. Whenever pattern recognition is vital to scientific inquiry, finite state machines can play an important role. Computer systems that can recognize voices, execute verbal commands or decipher handwriting are examples of finite state machines. A finite state machine is an imaginary machine with a finite number of well-defined resting states. The decisions as to what action needs to be taken are made by the state machine itself on the basis of the current state of the machine in combination with the systems input (e.g. the kinematic data). Although generic pattern recognition can in principle be implemented through logical statements (i.e. by concatenating sufficiently many IFs, ELSEs and THENs), the resulting code is generally hard to read, debug or modify. In the end, this approach is anything but clear, no matter how much effort is invested in laying out the code (Noble, 1995). Finite state machines provide a way to implement pattern recognition in a more transparent manner than logical concatenated nested IF-THEN statements. With finite state machines, one can model movements as sequences of states in spatio-temporal space, which provide us with the ability to implement the recognition of specific kinematic features and the appropriate actions in a structured and flexible way (Hong *et al.*, 2000). In our basketball experiment, specific kinematic landmarks of the shooting task had to be detected and appropriate actions (opening or shutting the goggles) had to be taken immediately. To implement and optimize this detection, both spatially and temporally, there were three main problems that had to be solved in the software.

Problem 1: conditional event control

On initiation of a trial, the shooter made a left-hand dribble, a step and a jump stop, after which he jumped up and took a jump shot. Given this elaborate task, the first problem to be solved was to make sure that not all movements of the right hand passing the line of sight (e.g. during the dribble) would trigger the goggles to open or shut. Only when the right hand passed the line of sight after the jump stop should a change of state of the goggles be triggered. In other words, when the system was not in the proper state, a movement of the hand through the line of sight was to be ignored. We defined the following subsequent states:

(a) start of trial;
(b) pre-jump: before the jump stop;
(c) below the line of sight: from jump stop until the hands passed the line of sight;
(d) above the line of sight: when the ball and hands passed the line of sight until the end of trial;
(e) end of trial.

As mentioned, the line of sight was defined as the line through the marker just above the eye and the marker just in front of the ear on the goggles (see Fig. 1, top). Passing the line of sight occurred when the marker on the ring finger of the right hand passed this line. This operationalization was sensitive enough for the current manipulation: to have a goggle switch in such a way that there was a clear distinction between before and after the ball and hands passed the line of sight.

After termination of a trial, a graphical display of movement trajectories was visible on the PC monitor. The display showed the sample numbers and coordinates of the markers on the foot, the goggles and the hand that were used to change the state of the state machine – that is, to shut or open the goggles. Together, this information provided invaluable feedback to the experimenter as to whether the conditional event control had been successful and whether the trial had to be repeated.

Problem 2: real-time retrieving and processing of kinematic data

The second problem concerned the need to deal effectively with the time constraints. Practically speaking, real-time applications fall into two primary types: those that respond in *hard* real-time and other *soft* real-time applications with less severe requirements. A hard real-time system must, without fail, provide a predictable response to some kind of event within a specified time window. A soft real-time system has reduced constraints on 'lateness', but still must operate quickly within fairly consistent time constraints (Microsoft Corporation, 1995).

The basketball jump shot application contained both hard and soft real-time components. Most of the processing algorithms used required data sampling at fixed time intervals, just as in the off-line data analysis. The hard real-time timekeeper in our set-up was the OPTOTRAK control unit that acquired three-dimensional data at a fixed time interval of 10 ms. The event control, on the other hand, was a soft real-time system running on the PC. In a pilot experiment, we determined that because of the physical dimensions of the ball (a diameter of 24 cm), it takes between 56 and 134 ms for different shooters (mean $\pm s$: 84 ± 23 ms; unpublished data obtained from video) to move the ball past the line of sight during shooting, implying that the goggle switch had to take place within about 50 ms. The time span of the processes needed to recognize the kinematic patterns and change the state of the goggles was 14–23 ms: 10 ms for one sample of the OPTOTRAK data (sampled hard real-time and buffered on the control unit), 3–10 ms for calculation of the algorithms and 1–3 ms for shutting or opening of the goggles. Thus, in all cases, the state change of the goggles was finished well within the natural and minimal boundaries of the task.

Problem 3: saving data for off-line analysis and event control

The third problem was to 'simultaneously' control events on the basis of on-line kinematic analyses and save the data to the hard disk of the PC for later analysis. OPTOTRAK enables a non-blocking spooling procedure for saving data. If the event control is idle, OPTOTRAK data are spooled from a buffer to disk. As soon as a new three-dimensional frame is ready, OPTOTRAK stops spooling and returns control to the event control loop. The event control loop is implemented as a finite state machine. One could call this a dual-process finite state machine, as described by Skahill (1996).

Evaluation of the method used

Limitations

As with any other optical system, the sensor has a limited viewing angle, which results in a restricted viewing range. In addition, 6 m is about the maximum distance at which reliable measurements are guaranteed. This has to be taken into account when designing an experiment in a (quasi-)field setting. It is possible to increase the field of view of OPTOTRAK by adding more position sensors, but this is not without costs.

Additional testing showed that, with four position sensors, errors of 1–2 mm and delays of 50 ms sometimes occurred. In short, reliable performance of the method depends on the combination of the number of position sensors, the number of markers and the sampling frequency, the limits of which should always be kept in mind.

Advantages

There are several advantages of controlling events using on-line movement registration. First, manipulations are coupled to movements of the actor, which is sometimes desirable given individual differences in executing perceptual-motor tasks. In our case, no matter how a shooter moved, the goggles changed state at a time appropriate for that person's movements. Second, the state machine we used was rather straightforward, with its sequential order of its various states. However, our state machine could easily be extended into a more complex finite state machine. OPTOTRAK could also be replaced by, or combined with, another registration device, such as a force plate or accelerometer. Furthermore, the controlled event (goggle change) could be replaced by another event, such as a change in computer display or (dis)appearance of an object. In fact, next to the goggle control we simultaneously controlled a light that indicated on video when the goggles were open or closed, so that we could determine the moment of ball release relative to the OPTOTRAK registration.

Within our faculty, the method is also implemented in experiments designed to gain insight into the biomechanical and neuro-physiological principles in the control of recovery reactions after tripping. The to-be-tripped-over obstacle pops up from the floor at a specific moment that is determined on the basis of characteristics of one or two steps before reaching the obstacle (M. Pijnappels, M.F. Bobbert and J.H. van Dieën, unpublished). This is also a powerful application of the method presented here in which data from different sources – OPTOTRAK, force plate and an electromyograph – are simultaneously gathered.

Another advantage of our method is that it provides experimenters with a high degree of control over events they wish to manipulate both during and after testing. As mentioned earlier, displaying the kinematic patterns on the PC monitor, including the features used to control the event manipulation, provides immediate feedback about the success of the manipulation on that particular trial. A typical advantage is also that the kinematic data are stored off-line for later use; for instance, for improving and refining the algorithms used to recognize movement patterns to make these algorithms more robust. If one were to use a manual switch to control events, this information would be lost.

Furthermore, the kinematic data can be analysed and reported for scientific purposes, in addition to other dependent variables, such as shooting percentages or other performance scores. After a brief summary of the results of Oudejans *et al.* (2002), we present some of these kinematic results in the remainder of the paper.

Results of the basketball experiment

Summary of the results of Oudejans et al. (2002)

Recall that we investigated shooting performance of expert male high-style shooters with vision occluded either before or after the ball and hands had passed the line of sight. Eight expert male shooters took shots under two experimental viewing conditions [namely, early vision (vision provided from trial initiation until the hands moved past the line of sight, and occluded during the final ~350 ms before ball release) and late vision (vision only provided during the final ~350 ms before ball release] and two control conditions (no vision and full vision). Late vision shooting (60.5%) appeared to be as good as shooting with full vision (61.5%), whereas early vision performance was severely and significantly impaired (30.0%) and not significantly different from shooting performance without vision (17.5%). That the shooters performed well with late vision only must mean that they used relevant visual information during the brief period that the goggles were open. Thus, contrary to what the findings of Vickers (1996) would imply for players with a low shooting style, having early vision did not result in good performance for the high-style shooters in our study. In contrast, when these shooters were given vision late, a good shooting performance followed. Thus, with only the last 350 ms of vision before ball release, the shooters with the high shooting style were able to maintain their performance. These results imply that the final shooting movements were controlled by continuous detection and use of visual information until ball release. With the methodology described in this paper, it was possible to determine not only that late viewing was sufficient for basketball jump shooting, but also that it was necessary.

New kinematic analyses

To establish the effect of shutting or opening the goggles in the course of action, additional analyses were performed on the kinematic data obtained using OPTOTRAK. The durations of the different phases of the shooting action were computed for each viewing condition to determine whether our manipulations of vision had any effect on the temporal patterning of the action. As a starting point, we took the instant of landing, after which we computed the durations of the periods between the following instants (see Fig. 2): landing (LA), when the goggles switched (GO), when the ball arrived at the ready position above the head (RP; before initiating the final shooting movements), when the final propulsion was initiated (FP), when peak height during the jump was reached (PH) and when the ball was released (BR). A one-way (condition: no vision, full vision, early vision, late vision) analysis of variance (ANOVA) with repeated measures was executed over the entire period, from landing to ball release. For the other periods, planned pairwise comparisons were performed to test for differences between different viewing conditions. A Bonferroni correction of the critical *P*-value was used to guard against inflation of Type I error rates. The *P*-values that are reported on the basis of this Bonferroni method are scaled to the 0.05 alpha-level, so that *P*-values smaller than 0.05 indicate a significant effect. Effect sizes (*ES*) were also computed, with values of 0.20, 0.50 and >0.80 indicating small, moderate and large effects, respectively (see Cohen, 1988; Mullineaux *et al.*, 2001). For one participant, the OPTOTRAK data did not allow computation of the moment at which the ball arrived in the ready position or of the moment at which the final movement was initiated. Therefore, the analyses involving either of these moments were done with seven instead of eight participants.

The analysis for the entire period, from landing to ball release, revealed a significant main effect for condition ($F_{3,21} = 13.5$, $P = 0.001$, $ES = 0.62$). Pairwise comparisons between conditions showed that in the late vision condition, the entire period lasted somewhat longer (626 ms) than with no vision (577 ms), full vision (585 ms) or early vision (571 ms) ($t_7 = -5.61$, $ES = 0.60$; $t_7 = -4.25$, $ES = 0.43$, $t_7 = -5.20$, $ES = 0.58$, respectively; all $P < 0.05$). To pin down these differences more precisely in time, additional analyses were done. Neither the planned pairwise comparisons on the period from landing to goggle switch, nor those on the period from goggle switch to the moment the ball was in the ready position, showed any significant differences between conditions (all $t < 2.15$), indicating that until the ball was in the ready position, no differences in temporal patterning of the movements were seen between conditions (see Fig. 2). The analyses of the period from ready position to ball release revealed differences between the late vision condition (238 ms) and the no vision (196 ms) and early vision (196 ms) conditions ($t_6 = -3.31$, $ES = 1.06$; $t_6 = -4.00$, $ES = 1.26$, respectively; both $P < 0.05$). More specific analyses of the period between ready position and the initiation of the final propulsion demonstrated only a marginally significant difference between the late vision (125 ms) and the early vision (87 ms) condition ($t_6 = -3.14$, $ES = 1.16$; $P = 0.06$), suggesting that, compared with early vision, with late vision shooters held the ball somewhat longer in the ready position before initiating the final propulsion movement. The final

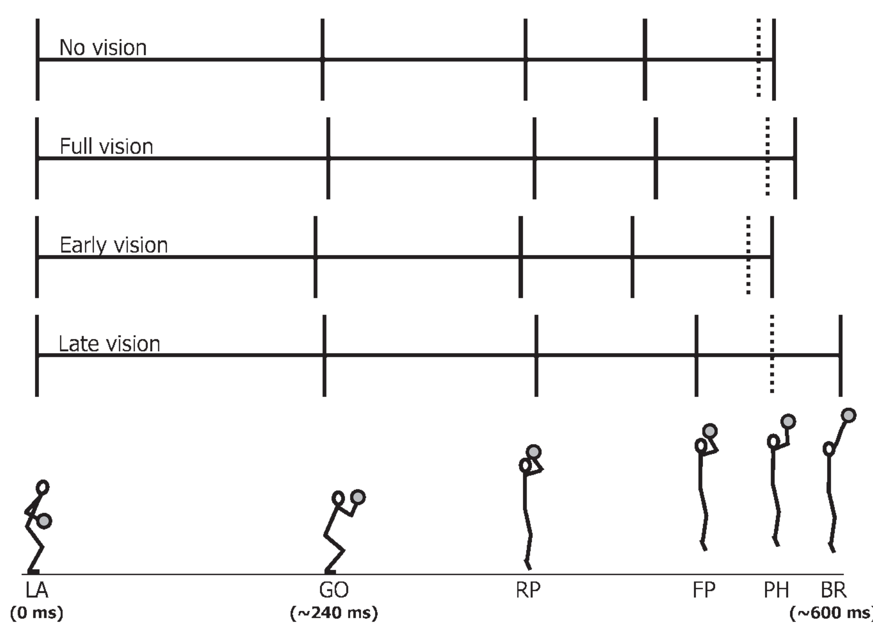

Fig. 2. Temporal sequence of phases of the shooting action after landing in the different viewing conditions. LA = moment of landing; GO = moment at which the goggles switched; RP = moment at which the ball arrived in the ready position above the head (before initiating the final shooting movements); FP = moment of initiation of the final propulsion movement; PH (dotted lines) = moment of peak height during the jump; BR = moment of ball release.

propulsion movement itself (from FP to BR) did not last longer in the late vision condition (112 ms) than in the no vision (103 ms), full vision (109 ms) or early vision (109 ms) conditions (all $t < 1.3$). Finally, planned pairwise comparisons of the period between the peak height during the jump and ball release revealed that the ball was released significantly later relative to peak height in the late vision condition (55 ms) than in the no vision (14 ms), full vision (22 ms) and early vision (19 ms) conditions ($t_7 = -5.13$, $ES = 0.98$; $t_7 = -4.66$, $ES = 0.64$; $t_7 = -4.08$, $ES = 0.70$, respectively; all $P < 0.05$).

In summary, in the late vision condition – especially relative to the early vision condition – shooters seemed to lengthen the in-flight period in which the hands and ball were held relatively stationary above eye level (ready position) before the final shooting movements (see also Fig. 2), thereby giving themselves just a little more viewing time. The duration of the final shooting movements was not different in different conditions. As a result of the longer rest phase in the late vision condition, the ball was eventually released on average 55 ms after peak jump height in that condition. This was in contrast to the other conditions, in which ball release occurred about 20 ms after the moment of peak jump height, implying that with late vision the descent of the centre of gravity had to be compensated for during the final shooting movements. Together, the results support the conclusion of Oudejans *et al.* (2002) that in jump shooting with a high style, visual information is effectively processed at least until initiation of the final acceleration phase, a little more than 100 ms before ball release, but possibly even during the final shooting movements, implying closed-loop rather than open-loop control of the shooting movements.

Concluding remarks

Manipulating experimental conditions on the basis of on-line movement registration has much potential for future research in the areas of motor control and learning and sport science. It may provide a new way for testing old problems that have to date been tested using contemporary technological developments. Eventually, it may even lead to new research questions. We are currently pursuing research in basketball jump shooting using this methodology to shed light on the possible interactions in complex human behaviour between different pathways (dorsal and ventral) for visual information processing in the central nervous system. In this case, on-line movement registration provides the most appropriate solution to control vision of the shooters during shooting movements.

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